VISIBLE NULLING INTERFEROMETER

Michael Shao, Eugene Serabyn, B. Martin Levine, Bertrand Mennesson, Thangasamy Velusamy

Jet Propulsion Laboratory/California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

ABSTRACT

The direct detection of Earthlike planets in the visible is a very challenging goal. This paper describes a new concept for visible direct detection of Earths using a nulling interferometer instrument behind a 4m telescope in space. The basic concept is described along with the key advantages of the nulling interferometer over more traditional approaches, an apodized aperture telescope or coronagraph. In the baseline design, a 4 beam nuller produces a very deep theta^4 null. With perfect optics, the stellar leakage is less than 1e-11 of the starlight at the location of the planet. With diffraction limited (lambda/20) telescope optics suppression of the starlight to ~1e-10 would be possible.

Keywords: Direct planet detection, nulling, coronagraph.

1. INTRODUCTION

The detection of planets beyond our own solar system is one of a few major scientific endeavors that have drawn widespread interest in both the science and technical communities and with the public at large. The field made major advances in the late 1990s with the discovery of Jovian sized planets around dozens of stars using radial velocity techniques. Presently there are over 100 known planets outside our solar system. The holy grail of this field is the detection of Earthlike planets, in the habitable zone.

In the 1990s the most promising technique seemed to be long-baseline interferometers in looking for thermal emission of Exo-Earths at 10um. The main advantage of looking at 10um, rather than the visible, is that the contrast ratio (star to planet flux) is only ~ 10^7 at 10um rather than 10^10. In addition at 11um, there is a prominent ozone band, which was an indicator for the presence of oxygen in the planet's atmosphere.

In the last 1~2 years, there has been considerable interest in revisiting the feasibility of visible light detection. The most often studied approaches have been coronagraphs and apodized aperture telescopes. We present here a third alternative, a nulling coronagraph (as opposed to a Lyot type coronagraph). The nulling coronagraph has several potentially very important advantages. First is very high starlight theoretical rejection for a planet 0.1 arcsec from the star. With perfect optics, starlight suppression of 10^-12 is possible and with lambda/20 optics 10^-10 suppression is possible.

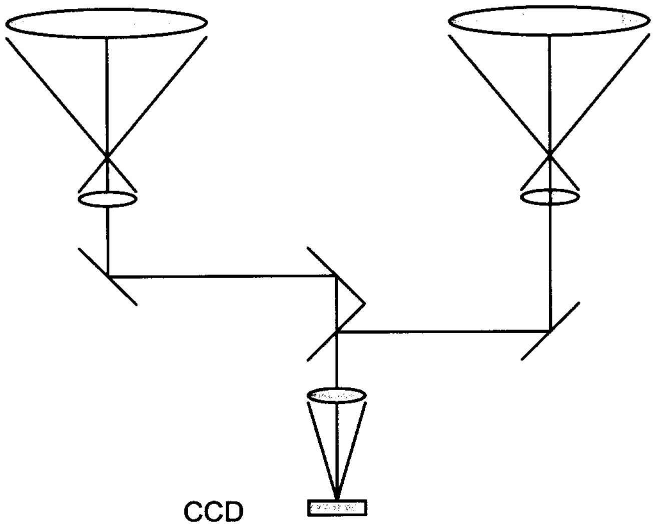
We present a preliminary concept of a 4m telescope with a nulling coronagraph that can detect Earthlike planets in a solar system analog at a distance of 10 parsec.

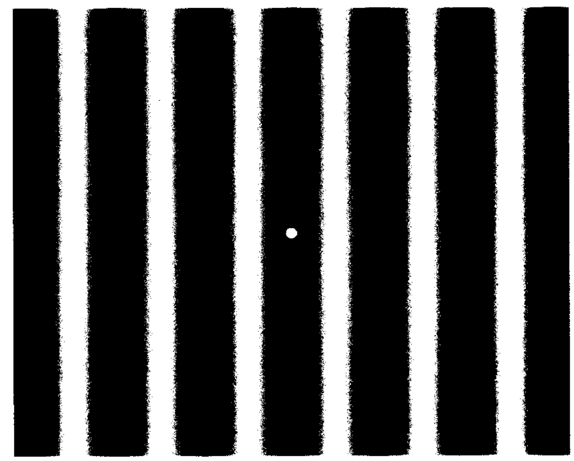
2. NULLER CONCEPT

1. Basic 2 element nulling interferometer

A nulling interferometer interferes the light from two apertures, destructively. This is shown in the figure below as a two-telescope interferometer. Light that is "on axis" is destructively interfered, but planet light "off axis" passes through the nuller and is detected. Behind the interferometer we can place a camera to image the field of view. The use of a camera for a visible nulling coronagraph is in contrast to an IR nulling interferometer where a single pixel detector is used.

It's important to understand what the nuller does to the camera image. The nuller places a transmission grating in the sky. The camera images the sky but the transmission of the camera/nuller depends on the position of the object in the sky. In this way the nulling coronagraph is similar to a regular lyot coronagraph where the transmission of the coronagraph is less when the light is blocked by the coronagraphic stop.



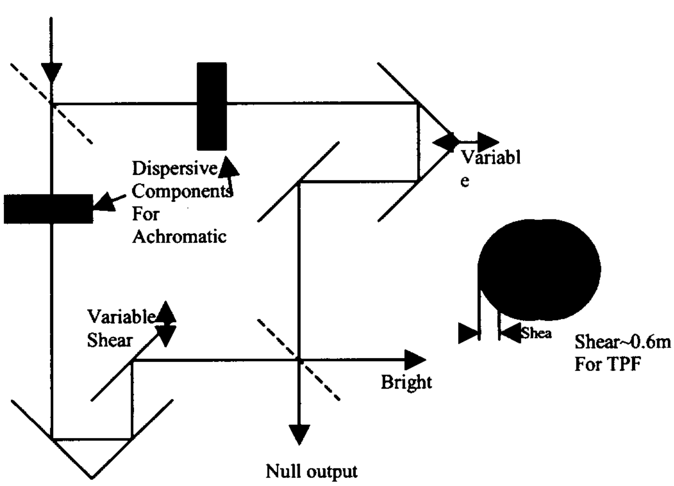


Transmission Pattern of Nuller
On the sky. (Star is at the center)

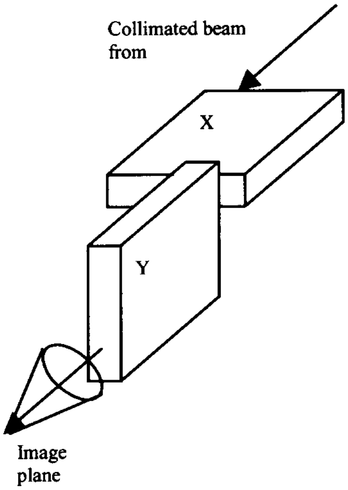
This optical configuration is not practical for planet detection because the baselines (separation) between telescopes are rather small ~ 60cm, while the needed collecting apertures are quite large ~4m. There are several other problems with this configuration. If the pathlengths of the above interferometer from the star to the beam combiner are exactly equal, the output of the interferometer is not zero; it's midway between zero and max. If one of the mirrors were translated to shift the fringe to a null, that null would only apply to 1 wavelength of light. The baseline (distance between the two telescopes) determines the spacing of the fringe pattern on the sky. The longer the baseline the smaller the spacing of the fringes. We need sufficient baseline to put the star on the center of the null, and the planet at the first bright fringe. In a two element nuller this baseline is $B = \lambda/(2\theta)$. Where θ is the angular separation between star-planet in radians. At a wavelength of 600nm, an Earth-Sun system at 10 parsec, θ is 0.1 arcsec, and B is 62cm.

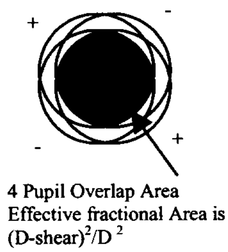
2. Finite diameter starlight leakage and the Machzender nuller

A simple 2-element null will have a sinusoidal transmission pattern. Exactly on axis, the transmission is zero, but slightly off axis, the transmission is $(1-\cos(k^*\phi))$ where $k= 2\pi B/\lambda$. A solar like star has a radius of 0.5 milliarcsec (mas) or 2.4e-9 radians and the leakage at the edge of the star is 3e-5, much brighter than the needed stellar rejection of 1e-9 to 1e-10. The solution to all of the above problems is shown in the figure below. The basic nulling coronagraph uses a modified Machzender interferometer that works in a collimated beam formed after the telescope focus.



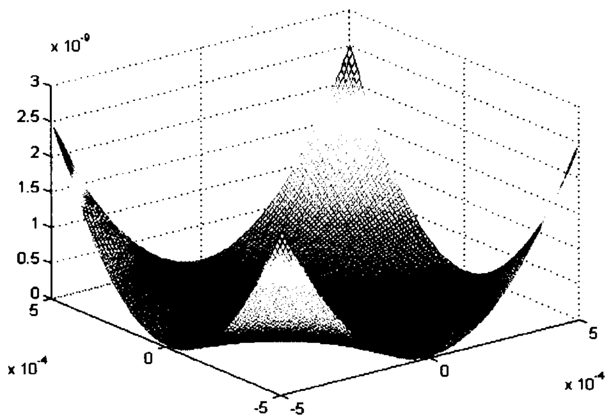
Modified Machzender Nulling



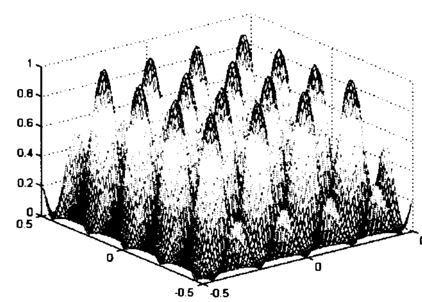


Note that a Machzender is used instead of a rotational shearing interferometer. A rotational shearing interferometer would form two images of the planet 180 deg apart. While this is annoying, the fatal flaw of a rotational shearing interferometer is that the effective baseline varies from zero to the diameter of the telescope. The modified Machzender interferometer splits the telescope pupil into two and recombines them with a "shear" the dispersive plates and the two arms are set to produce an achromatic "null" over a limited range of wavelengths (~25%). A second Machzender is used to split the pupil again and recombine them with a shear in the orthogonal direction.

The result is a four beam null pattern. The property of this type of 4 beam nulling interferometer was first studied in the context of a long baseline IR nulling interferometer. The "sky transmission" pattern is shown below.

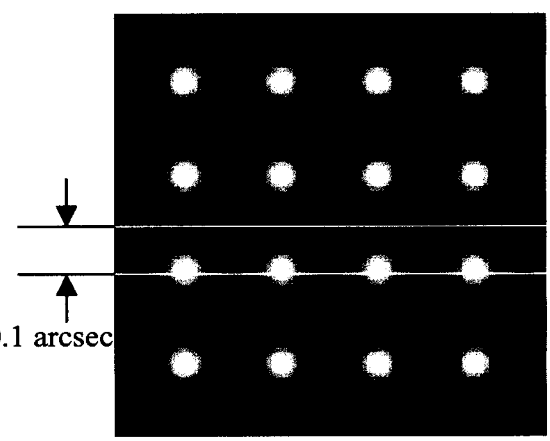


The center of the null pattern,
Scale +/- 0.5 milliarcsec
Finite diameter stellar leakage < 1e-9



Null Pattern Scale +/- 0.5 arcsec

Null Pattern on Sky

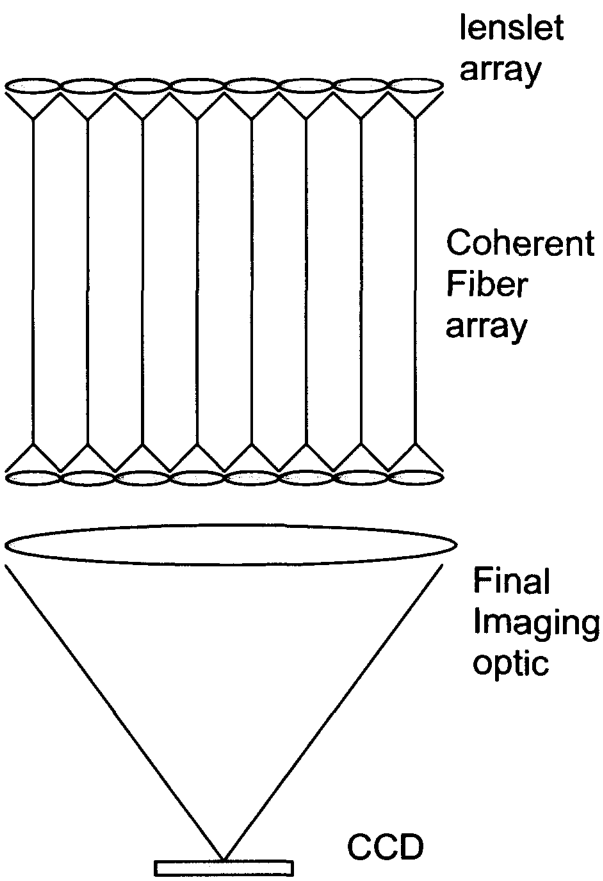


At the right is the sky transmission pattern over a field of ~1 arcsec. What's more important is the transmission pattern at the center of the field. The leakage in a 2 element null patter grows as θ^2, but the leakage in the 4 aperture nuller grows as θ ^4. The result is that the finite diameter of the star would leak less than ~1e-9 at the edge of the star.

The effective aperture of the nuller is slightly less than the diameter of the telescope. If the telescope is 4m in diameter and we use a 60cm shear, the effective diameter of the nuller is ~3.4m, approximately 72% of the area. In the case where the optics is perfect, the image at the camera after the nuller would be a star attenuated by ~ 1e-9 at the center of the field. Approximately ~3 airy rings out there would be the image of an Earthlike planet. The star's diffraction pattern at the location of the planet would be ~4e-12, the planet signal would be ~ 1e-10. Local zodical light would present a uniform background at a level of a ~2e-10.

3. Control of scattered light

Very high levels of starlight suppression require very accurate optical surfaces. The assumption that such precise optical surfaces are available, especially for 4m sized telescopes, needs to be examined. In the IR nulling interferometer, there is no need for ultra-precise surfaces. That need was eliminated by the introduction of a single mode optical fiber. If the output of a nulling interferometer is focused onto a single mode fiber, then inside the fiber, the only parameters that are important are the amplitude and phase of the electric field. If the amplitude and phase are properly matched, a very deep null can be achieved. In the IR a single mode spatial filter with say a 2m aperture would limit the field of view of an IR nulling interferometer to lambda/D, 10um/2m ~ 1arcsec. In the visible, a single mode fiber with a 4m telescope would not have sufficient field of view. To increase the field of view a coherent array of single mode fibers is needed as shown in the drawing below.



The pupil of the telescope would be reimaged onto a lenslet array with each lens in the lenslet array equivalent to 5~10 cm on the telescope primary. The field of view of this imaging system would be lambda/d, where d is 5~10cm. The field of view would be between 1 and 2 arcsec. The 4m telescope and the nuller optics will not be perfect and even with the single mode fiber, the starlight leakage is expected to be much larger than 1e-9. At JPL, we've seen nulls as deep as 1e-6 in the lab. We assume that further technology development results in improvement of that result. A null depth of 1e-7 would be sufficient for an "Earth detection" nulling coronagraph.

If the optics were "perfect" we'd have a 1e-9 null due to leakage of light around at the edge of the star. But for a 1e-7 null due to imperfect optics, the optical phase and amplitude at the output of the fiber will be due to slight imperfections in the nuller. The optical phase at the outputs of the N fibers will essentially be random. This random phase distribution means the 1e-7 of the starlight that is not suppressed will spread roughly uniformly across the field of view. If the fiber array consists of ~1000 fibers (corresponding to ~ 1 arcsec field of view) the 1e-7 stellar leakage will be spread across ~1000 pixels in the focal plane. The average stellar leakage per pixel would be 1e-10, roughly the light level of the planet.

The coherent fiber array means that if we feed a plane wave into the lenslet/fiber array, the output wavefront from the lenslets on the other side of the array will be distorted by no more than ~ lambda/10 rms. The wavefront errors of the lenslets and fiber array should be significantly smaller than a wavelength.

3. SYSTEM ISSUES

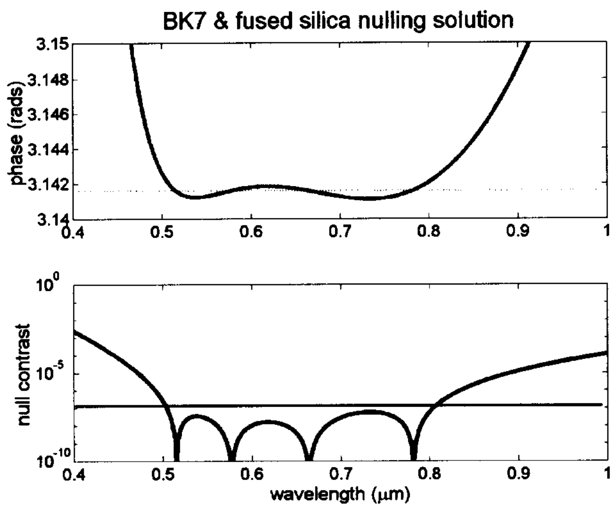
The previous section described the concept of the nulling coronagraph. This section discusses the system level issues such as the total throughput of the optical system, requirements on wavefront quality, wavefront stability, vibration levels, and expected signal to noise ratio.

1. Achieving and Maintaining a Deep Null

The electric field in the fiber from the 4 overlapping apertures, have to add to nearly zero. If we want a null of 1e-7 in intensity, the electric fields have to add to 3e-4. The effects that are important are amplitude, phase, and polarization orientation.

Type of defect	Max. contribution to null depth	Corresponding requirement
Piston (non zero residual OPD)	4e-8	44 pm rms @ 0.7μ m
Overall intensity relative mismatch	3e-8	6.9e-4
Differential phase shift between polarizations	1.5e-8	3.5e-4 rad
Differential rotation of polarization planes	1.5e-8	2.4e-4 rad

In addition the above 4 parameters must apply over a range of wavelengths. In a normal machzender interferometer, at zero OPD the fringe is a bright fringe. In order to achieve a null, a pi phase shift must be introduced. If we introduce a pi phase shift by moving a mirror that motion is exactly pi only at one wavelength. One method for generating a nearly pi shift over a range of wavelengths is to introduce dispersive elements into the interferometer. One dispersive element along with changing mirror position can generate exactly pi phase shift at exactly 3 wavelengths. In the example below two different types of dispersive glass are used (fused silica and BK7) that creates an exact pi phase shift at 4 wavelengths and an "almost" pi phase shift over the range 0.5 to 0.8 um wavelength range.



2. Measurement and control of critical parameters

The control of optical pathlength is performed by translating mirrors. Subnanometer motion of optical surfaces can be performed by a variety of devices, such as piezoelectric actuators. Intensity control is a bit more complex. The important detail is that the important parameter is intensity in the single mode fiber, not intensity throughout the telescope pupil. If one either "defocuses" the light into the fiber that can change the light coupled to the fiber. Through this and similar means, intensity control at the 6e-4 level is easily achieved. Differential phase shift between polarizations can be performed by rotating the dihedral mirrors in the modified machzender interferometer. Rotating the dihedral mirrors means keeping the angle between the two mirrors 90deg and rotating the unit in the plane of the interferometer. Rotating the dihedral mirrors in an orthogonal direction changes the plane of polarization.

The more challenging task is getting an error signal, or a signal that tells how much we should adjust each parameter mentioned in the above paragraph. An interferometer type nulling coronagraph in this regard has the advantage that the interferometer itself can readily be modified in a minor way to provide the error signal.

The final details of how to generate the error signals for null control will have to come from laboratory experiments and tests. What is described here is a first guess. OPD control is perhaps the easiest. One can modulate the path in one arm of the interferometer and synchronously demodulate the output of the nuller to minimize the light at the output of the nuller. Intensity control can be done with a mechanical chopper letting light from 1 arm through to the detector at a time. Polarization phase shift can be measured by putting a rotating polarizer in front of the detector and measuring the phase shift or OPD change with polarization. Polarization plane rotation can be measured by looking at a star off axis. The centroid of the overlapping star images will spread as the object goes off axis. Finally chromatic performance of the nuller can be diagnosed by putting narrow band filters at several wavelengths in front of the detector.

3. Overall Sensitivity

The coronagraphic nuller has different sensitivity in the "search" mode than in the "spectroscopy" mode. In the search mode, we don't know where the planet is. The transmission of the "null" pattern means that parts of the sky besides the star are "nulled". If a planet is in one of these areas, the planet will not be seen. So in search mode we have to rotate the telescope or nuller or both to cover all of the sky. This is similar to some apodized aperture telescope designs where the apodization function is not circularly symmetric. The average transmission of the null pattern is ¼. The time to search the whole sky is 4 times the time needed to detect a planet that is "most favorably" placed.

If the planet is at one of the "peaks" in the nuller transmission function, its light is totally unattenuated through the nuller. One can roughly estimate the transmission of the nulling coronagraph by making assumptions on the performance of the individual optical elements (e.g. 98% for mirror reflectivity).

Reflective and transmissive optics	70%
Beam splitters (R*T)	96%
Fiber coupling efficiency	60% (includes lenslet fill factor)
CCD QE in 0.5~0.8 band	75%
Effective collecting area	9 sq meters (4m telescope, null overlap area)
Total effective collecting area*QE	2.7 sq meters

The diff limit of a 3.4m telescope is ~ 40mas. The local zodi background would then be ~29 mag/pixel. This is brighter than either the scattered starlight or the planet. The SNR would be planet signal/sqrt(zodi+planet+scattered starlight). The planet would be a 30-mag object, the scattered starlight an average of a 30mag object per pixel and the zodi a background of 29mag/pixel. The time to get SNR=5 for a planet in the "clear" spot of the nulling pattern would be less than 45 minutes and the total time to search the area from a radius of 0.1 arcsec to 0.5 arcsec would be 4 times that, a bit more than 2.7 hours. The assumptions above are perhaps optimistic but even 10 hours would not be prohibitively long.

The need for a 4m aperture is not driven by photon flux, but by the need to have enough angular resolution after losing 60cm to beam shear, to put the planet 2 pixels from the star.

Spectroscopy at a spectral resolution of 100, and a SNR of 5 per spectral bin would take ~25 times longer than the search.

4. SUMMARY

We've presented a new concept for a visible coronagraph adapting nulling technology originally developed for the IR interferometer for exo-planet detection. This concept has several potential significant advantages.

1) Much deeper suppression of starlight (assuming perfect optics) starlight at planet location is 4e-12 if the optics were perfect.
2) A smaller telescope (4m) for an Earth-Sun planet at 10 pc.
3) Full aperture wavefront error of the telescope can be ~lambda/20
4) Moderately mature technology, 1e-6 null demonstrated in the lab, need 1e-7 for the flight mission
5) With 1e-7 nulls, scattered light is 1e-10/pixel, planet light/scattered light ratio of 1
6) With the above properties, there exists the possibility that direct detection at visible/near IR wavelengths of Earths within 10pc of the sun is possible with an instrument on NGST, an already approved NASA mission.

ACKNOWLEDGEMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

REFERENCES

1. Angel, R., (1990), "Use of a 16-m Telescope to Detect Earthlike Planets," Proceedings of the Workshop on The Next Generation Space Telescope, P. Bely and C. Burrows, eds., Space Telescope Science Institute, pp. 81–94.
2. Angel, J.R.P, and Woolf, N.J., (1997),"An Imaging Nulling Interferometer To Study Extrasolar Planets,"Astrophysical Journal, v475, pp. 373-379.
3. Gaffey, M. J., J. F. Bell, and D. P. Cruikshank, (1989), Reflectance spectroscopy and asteroid surface mineralogy. In Asteroids II, Binzel et al., eds., U. Arizona Press, Tucson, pp. 128–147.
4. Karkoschka, E., (1994), Spectrophotometry of the Jovian planets and Titan at 300-nm to 1000-nm wavelength: The methane spectrum. Icarus, v111, 174–192.
5. Lee, M. & Peale S., (2001), Evolution of the GJ876 Planets into the 2:1 Orbital Resonance. BAAS, 34, 3.03
6. Levison, H. F., Dones, L., Canup, R., Agnor, C., and Duncan, M. J., (2001), The Role of Giant Planets in Terrestrial Planet Formation. In 32nd Annual Lunar and Planetary Science Conference, March 12–16, 2001, Houston, Texas, abstract no. 1232.

7. Malbet, F.,Yu, J., Shao, (1995), M., Pub Astron Soc Pacific, V107, pp. 386–398, April 1995.
8. Marley, and C. M. Sharp, (2000), The near-infrared and optical spectra of methane dwarfs and brown dwarfs. Astrophys. J. v531, pp. 438–446.
9. Meadows, V. et al., (2000), Astronomical detection of biosignatures from extrasolar planets, JPL/Caltech proposal to the NASA Astrobiology Institute CAN–00–OSS–01.
10. Menneson, B., and Mariotti, J.M., (1997), "Array Configurations for a Space Infrared Nulling Interferometer Dedicated to the Search for Earthlike Extrasolar Planets", Icarus, v128, pp. 202–212.
11. Mennesson B.,Ollivier M., and Ruilier C., (2002), "On the use of single-mode waveguides to correct the optical defects of a nulling interferometer", J. Opt. Soc. Am. A, Feb 2002.
12. Morgan, R., Burge, J., and Woolf, N., (2000), "Nulling Interferometric Beam Combiner Utilizing Dielectric Plates" Experimental Results in the Visible Broadband SPIE v4006.
13. Saumon D., Hubbard W.B., Burrows A. et al., (1996), ApJ 460, 993.
14. Serabyn, E., Wallace, J.K., Hardy, G.J., Schwindthin, E.G.H., and Nguyen, (1999), "Deep Nulling of Visible LASER Light", Appl. Opt., v38, p7128.
15. Serabyn, E. and Colavita, M.M., (2001),"Fully Symmetric Nulling Beam Combiners", Applied Optics, v40, pp. 1668–1671.
16. Shao, M.,(1991), "Hubble Extra Solar Planet Interferometer", SPIE v1494.
17. Sudarsky, D., A. Burrows, and P. Pinto. (2000), Albedo and reflection spectra of extrasolar giant planets. Astrophys. J. v538, 885--903.
18. Wallace, K., Hardy, G, and Serabyn, E., (2000), "Deep and stable interferometric nulling of broadband light with implications for observing planets around nearby stars", Nature, v406.
19. Wu, Y., and Goldreich, P., (2001), Tidal evolution of the planetary system around HD 83443. Astrophys. J. submitted

VISIBLE NULLING INTERFEROMETER

Michael Shao, Eugene Serabyn, B. Martin Levine, Bertrand Mennesson, Thangasamy Velusamy

Jet Propulsion Laboratory/California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

ABSTRACT

The direct detection of Earthlike planets in the visible is a very challenging goal. This paper describes a new concept for visible direct detection of Earths using a nulling interferometer instrument behind a 4m telescope in space. The basic concept is described along with the key advantages of the nulling interferometer over more traditional approaches, an apodized aperture telescope or coronagraph. In the baseline design, a 4 beam nuller produces a very deep theta^4 null. With perfect optics, the stellar leakage is less than 1e-11 of the starlight at the location of the planet. With diffraction limited (lambda/20) telescope optics suppression of the starlight to ~1e-10 would be possible.

Keywords: Direct planet detection, nulling, coronagraph.

1. INTRODUCTION

The detection of planets beyond our own solar system is one of a few major scientific endeavors that have drawn widespread interest in both the science and technical communities and with the public at large. The field made major advances in the late 1990s with the discovery of Jovian sized planets around dozens of stars using radial velocity techniques. Presently there are over 100 known planets outside our solar system. The holy grail of this field is the detection of Earthlike planets, in the habitable zone.

In the 1990s the most promising technique seemed to be long-baseline interferometers in looking for thermal emission of Exo-Earths at 10um. The main advantage of looking at 10um, rather than the visible, is that the contrast ratio (star to planet flux) is only ~ 10^7 at 10um rather than 10^10. In addition at 11um, there is a prominent ozone band, which was an indicator for the presence of oxygen in the planet's atmosphere.

In the last 1~2 years, there has been considerable interest in revisiting the feasibility of visible light detection. The most often studied approaches have been coronagraphs and apodized aperture telescopes. We present here a third alternative, a nulling coronagraph (as opposed to a Lyot type coronagraph). The nulling coronagraph has several potentially very important advantages. First is very high starlight theoretical rejection for a planet 0.1 arcsec from the star. With perfect optics, starlight suppression of 10^-12 is possible and with lambda/20 optics 10^-10 suppression is possible.

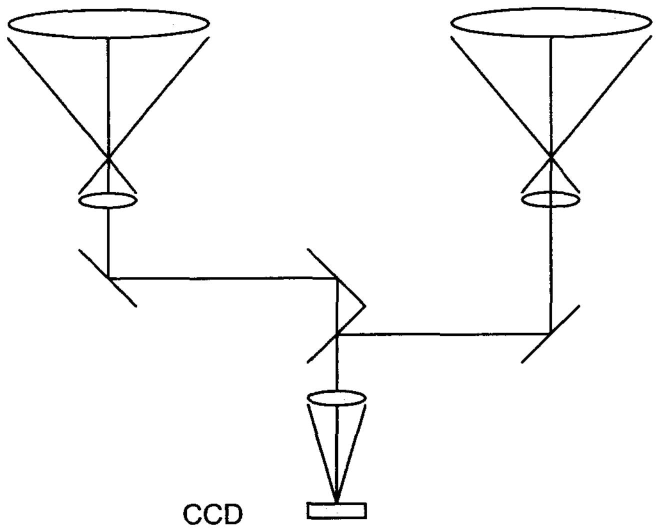
We present a preliminary concept of a 4m telescope with a nulling coronagraph that can detect Earthlike planets in a solar system analog at a distance of 10 parsec.

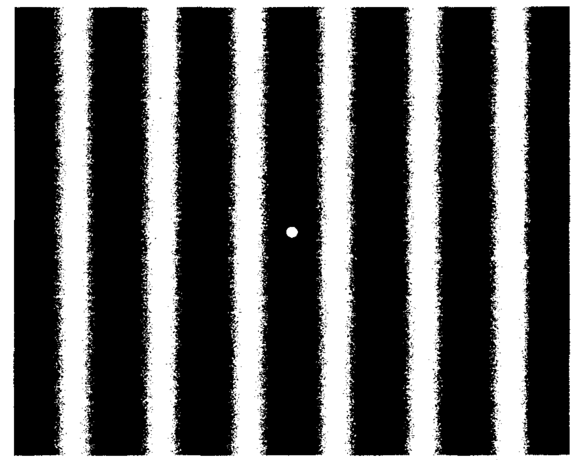
2. NULLER CONCEPT

1. Basic 2 element nulling interferometer

A nulling interferometer interferes the light from two apertures, destructively. This is shown in the figure below as a two-telescope interferometer. Light that is "on axis" is destructively interfered, but planet light "off axis" passes through the nuller and is detected. Behind the interferometer we can place a camera to image the field of view. The use of a camera for a visible nulling coronagraph is in contrast to an IR nulling interferometer where a single pixel detector is used.

It's important to understand what the nuller does to the camera image. The nuller places a transmission grating in the sky. The camera images the sky but the transmission of the camera/nuller depends on the position of the object in the sky. In this way the nulling coronagraph is similar to a regular lyot coronagraph where the transmission of the coronagraph is less when the light is blocked by the coronagraphic stop.



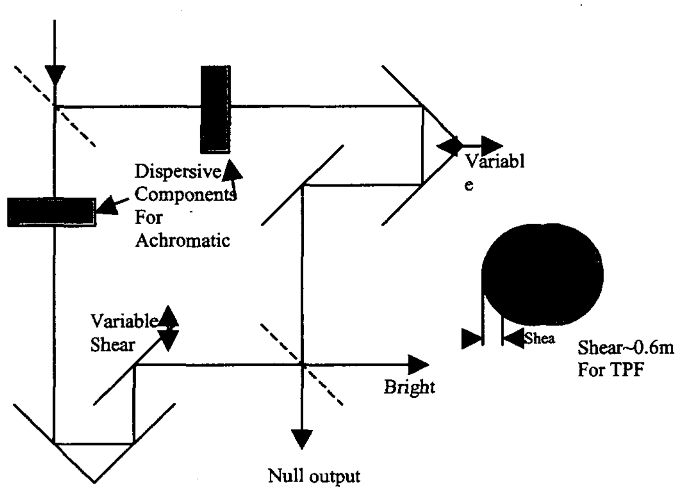


Transmission Pattern of Nuller
On the sky. (Star is at the center)

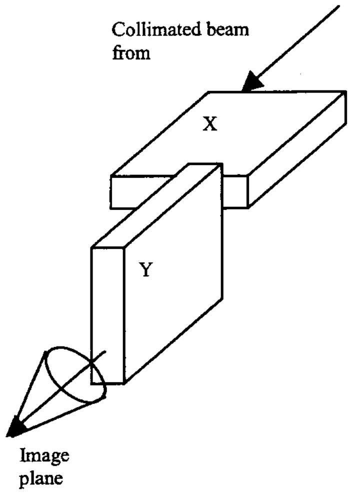
This optical configuration is not practical for planet detection because the baselines (separation) between telescopes are rather small ~ 60cm, while the needed collecting apertures are quite large ~4m. There are several other problems with this configuration. If the pathlengths of the above interferometer from the star to the beam combiner are exactly equal, the output of the interferometer is not zero; it's midway between zero and max. If one of the mirrors were translated to shift the fringe to a null, that null would only apply to 1 wavelength of light. The baseline (distance between the two telescopes) determines the spacing of the fringe pattern on the sky. The longer the baseline the smaller the spacing of the fringes. We need sufficient baseline to put the star on the center of the null, and the planet at the first bright fringe. In a two element nuller this baseline is $B = \lambda/(2\theta)$. Where θ is the angular separation between star-planet in radians. At a wavelength of 600nm, an Earth-Sun system at 10 parsec, θ is 0.1 arcsec, and B is 62cm.

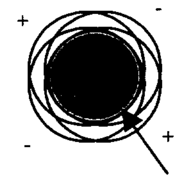
2. Finite diameter starlight leakage and the Machzender nuller

A simple 2-element null will have a sinusoidal transmission pattern. Exactly on axis, the transmission is zero, but slightly off axis, the transmission is $(1-\cos(k*\phi))$ where $k= 2\pi B/\lambda$. A solar like star has a radius of 0.5 milliarcsec (mas) or 2.4e-9 radians and the leakage at the edge of the star is 3e-5, much brighter than the needed stellar rejection of 1e-9 to 1e-10. The solution to all of the above problems is shown in the figure below. The basic nulling coronagraph uses a modified Machzender interferometer that works in a collimated beam formed after the telescope focus.



Modified Machzender Nulling

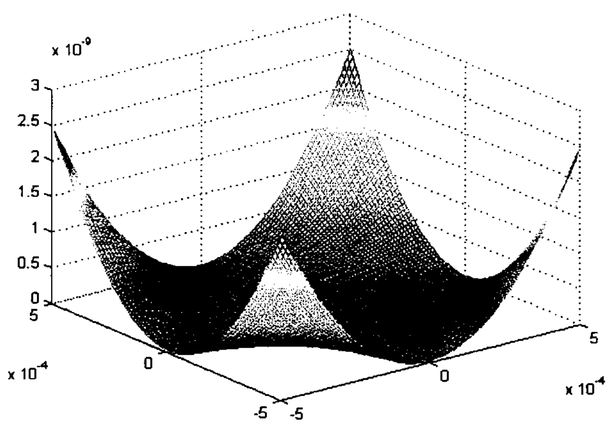


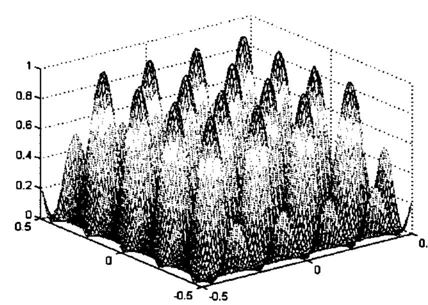


4 Pupil Overlap Area
Effective fractional Area is
$(D\text{-shear})^2/D^2$

Note that a Machzender is used instead of a rotational shearing interferometer. A rotational shearing interferometer would form two images of the planet 180 deg apart. While this is annoying, the fatal flaw of a rotational shearing interferometer is that the effective baseline varies from zero to the diameter of the telescope. The modified Machzender interferometer splits the telescope pupil into two and recombines them with a "shear" the dispersive plates and the two arms are set to produce an achromatic "null" over a limited range of wavelengths (~25%). A second Machzender is used to split the pupil again and recombine them with a shear in the orthogonal direction.

The result is a four beam null pattern. The property of this type of 4 beam nulling interferometer was first studied in the context of a long baseline IR nulling interferometer. The "sky transmission" pattern is shown below.

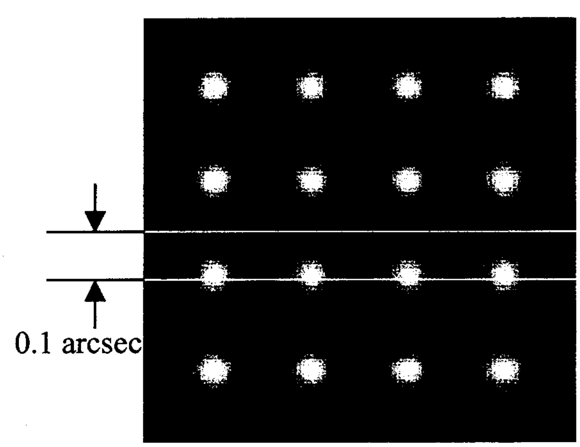




Null Pattern Scale +/- 0.5 arcsec

The center of the null pattern,
Scale +/- 0.5 milliarcsec
Finite diameter stellar leakage < 1e-9

Null Pattern on Sky

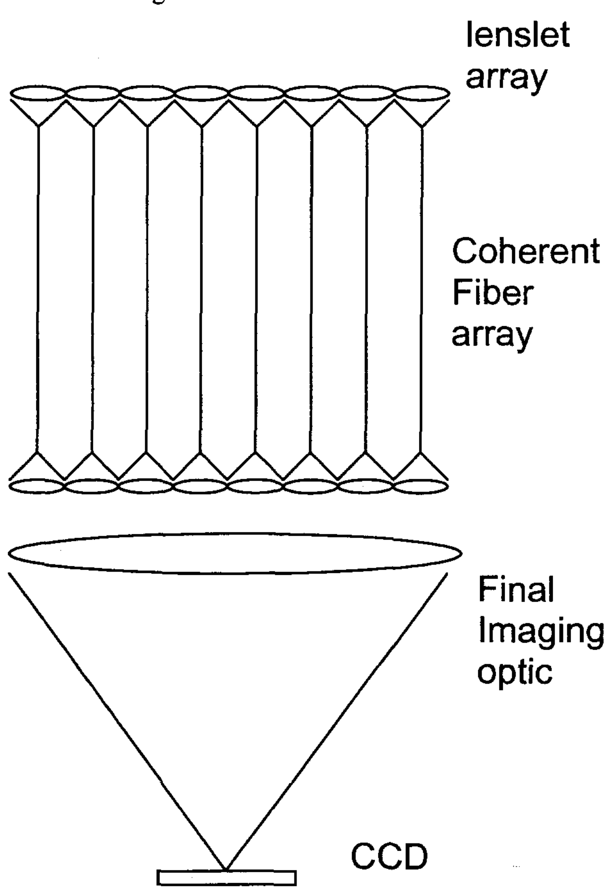


At the right is the sky transmission pattern over a field of ~1 arcsec. What's more important is the transmission pattern at the center of the field. The leakage in a 2 element null patter grows as θ^2, but the leakage in the 4 aperture nuller grows as θ ^4. The result is that the finite diameter of the star would leak less than ~1e-9 at the edge of the star.

The effective aperture of the nuller is slightly less than the diameter of the telescope. If the telescope is 4m in diameter and we use a 60cm shear, the effective diameter of the nuller is ~3.4m, approximately 72% of the area. In the case where the optics is perfect, the image at the camera after the nuller would be a star attenuated by ~ 1e-9 at the center of the field. Approximately ~3 airy rings out there would be the image of an Earthlike planet. The star's diffraction pattern at the location of the planet would be ~4e-12, the planet signal would be ~ 1e-10. Local zodical light would present a uniform background at a level of a ~2e-10.

3. Control of scattered light

Very high levels of starlight suppression require very accurate optical surfaces. The assumption that such precise optical surfaces are available, especially for 4m sized telescopes, needs to be examined. In the IR nulling interferometer, there is no need for ultra-precise surfaces. That need was eliminated by the introduction of a single mode optical fiber. If the output of a nulling interferometer is focused onto a single mode fiber, then inside the fiber, the only parameters that are important are the amplitude and phase of the electric field. If the amplitude and phase are properly matched, a very deep null can be achieved. In the IR a single mode spatial filter with say a 2m aperture would limit the field of view of an IR nulling interferometer to lambda/D, 10um/2m ~ 1arcsec. In the visible, a single mode fiber with a 4m telescope would not have sufficient field of view. To increase the field of view a coherent array of single mode fibers is needed as shown in the drawing below.



The pupil of the telescope would be reimaged onto a lenslet array with each lens in the lenslet array equivalent to 5~10 cm on the telescope primary. The field of view of this imaging system would be lambda/d, where d is 5~10cm. The field of view would be between 1 and 2 arcsec. The 4m telescope and the nuller optics will not be perfect and even with the single mode fiber, the starlight leakage is expected to be much larger than 1e-9. At JPL, we've seen nulls as deep as 1e-6 in the lab. We assume that further technology development results in improvement of that result. A null depth of 1e-7 would be sufficient for an "Earth detection" nulling coronagraph.

If the optics were "perfect" we'd have a 1e-9 null due to leakage of light around at the edge of the star. But for a 1e-7 null due to imperfect optics, the optical phase and amplitude at the output of the fiber will be due to slight imperfections in the nuller. The optical phase at the outputs of the N fibers will essentially be random. This random phase distribution means the 1e-7 of the starlight that is not suppressed will spread roughly uniformly across the field of view. If the fiber array consists of ~1000 fibers (corresponding to ~ 1 arcsec field of view) the 1e-7 stellar leakage will be spread across ~1000 pixels in the focal plane. The average stellar leakage per pixel would be 1e-10, roughly the light level of the planet.

The coherent fiber array means that if we feed a plane wave into the lenslet/fiber array, the output wavefront from the lenslets on the other side of the array will be distorted by no more than ~ lambda/10 rms. The wavefront errors of the lenslets and fiber array should be significantly smaller than a wavelength.

3. SYSTEM ISSUES

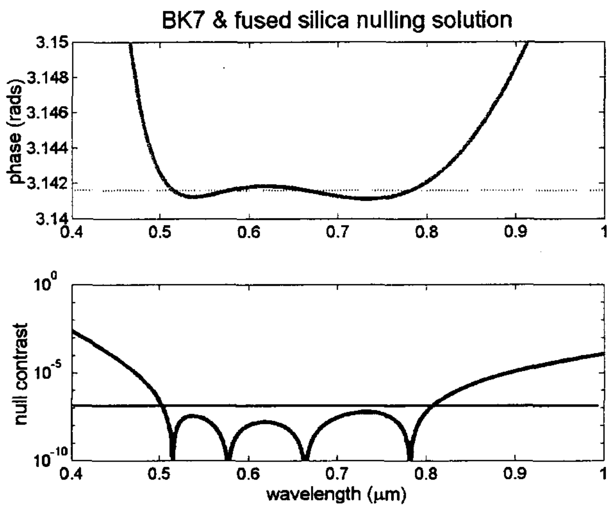
The previous section described the concept of the nulling coronagraph. This section discusses the system level issues such as the total throughput of the optical system, requirements on wavefront quality, wavefront stability, vibration levels, and expected signal to noise ratio.

1. Achieving and Maintaining a Deep Null

The electric field in the fiber from the 4 overlapping apertures, have to add to nearly zero. If we want a null of 1e-7 in intensity, the electric fields have to add to 3e-4. The effects that are important are amplitude, phase, and polarization orientation.

Type of defect	Max. contribution to null depth	Corresponding requirement
Piston (non zero residual OPD)	4e-8	44 pm rms @ 0.7μ m
Overall intensity relative mismatch	3e-8	6.9e-4
Differential phase shift between polarizations	1.5e-8	3.5e-4 rad
Differential rotation of polarization planes	1.5e-8	2.4e-4 rad

In addition the above 4 parameters must apply over a range of wavelengths. In a normal machzender interferometer, at zero OPD the fringe is a bright fringe. In order to achieve a null, a pi phase shift must be introduced. If we introduce a pi phase shift by moving a mirror that motion is exactly pi only at one wavelength. One method for generating a nearly pi shift over a range of wavelengths is to introduce dispersive elements into the interferometer. One dispersive element along with changing mirror position can generate exactly pi phase shift at exactly 3 wavelengths. In the example below two different types of dispersive glass are used (fused silica and BK7) that creates an exact pi phase shift at 4 wavelengths and an "almost" pi phase shift over the range 0.5 to 0.8 um wavelength range.



2. Measurement and control of critical parameters

The control of optical pathlength is performed by translating mirrors. Subnanometer motion of optical surfaces can be performed by a variety of devices, such as piezoelectric actuators. Intensity control is a bit more complex. The important detail is that the important parameter is intensity in the single mode fiber, not intensity throughout the telescope pupil. If one either "defocuses" the light into the fiber that can change the light coupled to the fiber. Through this and similar means, intensity control at the 6e-4 level is easily achieved. Differential phase shift between polarizations can be performed by rotating the dihedral mirrors in the modified machzender interferometer. Rotating the dihedral mirrors means keeping the angle between the two mirrors 90deg and rotating the unit in the plane of the interferometer. Rotating the dihedral mirrors in an orthogonal direction changes the plane of polarization.

The more challenging task is getting an error signal, or a signal that tells how much we should adjust each parameter mentioned in the above paragraph. An interferometer type nulling coronagraph in this regard has the advantage that the interferometer itself can readily be modified in a minor way to provide the error signal.

The final details of how to generate the error signals for null control will have to come from laboratory experiments and tests. What is described here is a first guess. OPD control is perhaps the easiest. One can modulate the path in one arm of the interferometer and synchronously demodulate the output of the nuller to minimize the light at the output of the nuller. Intensity control can be done with a mechanical chopper letting light from 1 arm through to the detector at a time. Polarization phase shift can be measured by putting a rotating polarizer in front of the detector and measuring the phase shift or OPD change with polarization. Polarization plane rotation can be measured by looking at a star off axis. The centroid of the overlapping star images will spread as the object goes off axis. Finally chromatic performance of the nuller can be diagnosed by putting narrow band filters at several wavelengths in front of the detector.

3. Overall Sensitivity

The coronagraphic nuller has different sensitivity in the "search" mode than in the "spectroscopy" mode. In the search mode, we don't know where the planet is. The transmission of the "null" pattern means that parts of the sky besides the star are "nulled". If a planet is in one of these areas, the planet will not be seen. So in search mode we have to rotate the telescope or nuller or both to cover all of the sky. This is similar to some apodized aperture telescope designs where the apodization function is not circularly symmetric. The average transmission of the null pattern is ¼. The time to search the whole sky is 4 times the time needed to detect a planet that is "most favorably" placed.

If the planet is at one of the "peaks" in the nuller transmission function, its light is totally unattenuated through the nuller. One can roughly estimate the transmission of the nulling coronagraph by making assumptions on the performance of the individual optical elements (e.g. 98% for mirror reflectivity).

Reflective and transmissive optics	70%
Beam splitters (R*T)	96%
Fiber coupling efficiency	60% (includes lenslet fill factor)
CCD QE in 0.5~0.8 band	75%
Effective collecting area	9 sq meters (4m telescope, null overlap area)
Total effective collecting area*QE	2.7 sq meters

The diff limit of a 3.4m telescope is ~ 40mas. The local zodi background would then be ~29 mag/pixel. This is brighter than either the scattered starlight or the planet. The SNR would be planet signal/sqrt(zodi+planet+scattered starlight). The planet would be a 30-mag object, the scattered starlight an average of a 30mag object per pixel and the zodi a background of 29mag/pixel. The time to get SNR=5 for a planet in the "clear" spot of the nulling pattern would be less than 45 minutes and the total time to search the area from a radius of 0.1 arcsec to 0.5 arcsec would be 4 times that, a bit more than 2.7 hours. The assumptions above are perhaps optimistic but even 10 hours would not be prohibitively long.

The need for a 4m aperture is not driven by photon flux, but by the need to have enough angular resolution after losing 60cm to beam shear, to put the planet 2 pixels from the star.

Spectroscopy at a spectral resolution of 100, and a SNR of 5 per spectral bin would take ~25 times longer than the search.

4. SUMMARY

We've presented a new concept for a visible coronagraph adapting nulling technology originally developed for the IR interferometer for exo-planet detection. This concept has several potential significant advantages.

1) Much deeper suppression of starlight (assuming perfect optics) starlight at planet location is 4e-12 if the optics were perfect.
2) A smaller telescope (4m) for an Earth-Sun planet at 10 pc.
3) Full aperture wavefront error of the telescope can be ~lambda/20
4) Moderately mature technology, 1e-6 null demonstrated in the lab, need 1e-7 for the flight mission
5) With 1e-7 nulls, scattered light is 1e-10/pixel, planet light/scattered light ratio of 1
6) With the above properties, there exists the possibility that direct detection at visible/near IR wavelengths of Earths within 10pc of the sun is possible with an instrument on NGST, an already approved NASA mission.

ACKNOWLEDGEMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

REFERENCES

1. Angel, R., (1990), "Use of a 16-m Telescope to Detect Earthlike Planets," Proceedings of the Workshop on The Next Generation Space Telescope, P. Bely and C. Burrows, eds., Space Telescope Science Institute, pp. 81–94.
2. Angel, J.R.P, and Woolf, N.J., (1997),"An Imaging Nulling Interferometer To Study Extrasolar Planets,"Astrophysical Journal, v475, pp. 373-379.
3. Gaffey, M. J., J. F. Bell, and D. P. Cruikshank, (1989), Reflectance spectroscopy and asteroid surface mineralogy. In Asteroids II, Binzel et al., eds., U. Arizona Press, Tucson, pp. 128–147.
4. Karkoschka, E., (1994), Spectrophotometry of the Jovian planets and Titan at 300-nm to 1000-nm wavelength: The methane spectrum. Icarus, v111, 174–192.
5. Lee, M. & Peale S., (2001), Evolution of the GJ876 Planets into the 2:1 Orbital Resonance. BAAS, 34, 3.03
6. Levison, H. F., Dones, L., Canup, R., Agnor, C., and Duncan, M. J., (2001), The Role of Giant Planets in Terrestrial Planet Formation. In 32nd Annual Lunar and Planetary Science Conference, March 12–16, 2001, Houston, Texas, abstract no. 1232.

7. Malbet, F.,Yu, J., Shao, (1995), M., Pub Astron Soc Pacific, V107, pp. 386–398, April 1995.
8. Marley, and C. M. Sharp, (2000), The near-infrared and optical spectra of methane dwarfs and brown dwarfs. Astrophys. J. v531, pp. 438–446.
9. Meadows, V. et al., (2000), Astronomical detection of biosignatures from extrasolar planets, JPL/Caltech proposal to the NASA Astrobiology Institute CAN–00–OSS–01.
10. Menneson, B., and Mariotti, J.M., (1997), "Array Configurations for a Space Infrared Nulling Interferometer Dedicated to the Search for Earthlike Extrasolar Planets", Icarus, v128, pp. 202–212.
11. Mennesson B.,Ollivier M., and Ruilier C., (2002), "On the use of single-mode waveguides to correct the optical defects of a nulling interferometer", J. Opt. Soc. Am. A, Feb 2002.
12. Morgan, R., Burge, J., and Woolf, N., (2000), "Nulling Interferometric Beam Combiner Utilizing Dielectric Plates" Experimental Results in the Visible Broadband SPIE v4006.
13. Saumon D., Hubbard W.B., Burrows A. et al., (1996), ApJ 460, 993.
14. Serabyn, E., Wallace, J.K., Hardy, G.J., Schwindthin, E.G.H., and Nguyen, (1999), "Deep Nulling of Visible LASER Light", Appl. Opt., v38, p7128.
15. Serabyn, E. and Colavita, M.M., (2001),"Fully Symmetric Nulling Beam Combiners", Applied Optics, v40, pp. 1668–1671.
16. Shao, M.,(1991), "Hubble Extra Solar Planet Interferometer", SPIE v1494.
17. Sudarsky, D., A. Burrows, and P. Pinto. (2000), Albedo and reflection spectra of extrasolar giant planets. Astrophys. J. v538, 885--903.
18. Wallace, K., Hardy, G, and Serabyn, E., (2000), "Deep and stable interferometric nulling of broadband light with implications for observing planets around nearby stars", Nature, v406.
19. Wu, Y., and Goldreich, P., (2001), Tidal evolution of the planetary system around HD 83443. Astrophys. J. submitted